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WIND TUNNEL TECHNOLOGY FOR THE DEVELOPMENT OF FUTURE COMMERCIAL AIRCRAFT

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16. Abstract Requirements for new technologies in the area of civil aircraft design are mainly related to the high costs involved in the purchase of modern, fuel-saving aircraft. A second important factor is the long-term rise in the price of fuel. The demonstration of the benefits of new technologies, as far as these are related to aerodynamics, will, for the foreseeable future, still be based on wind-tunnel measurements. Theoretical computation methods are very successfully used in design work, wing optimization, and an estimation of the Reynolds number effect. However, wind-tunnel tests are still needed to verify the feasibility of the considered concepts. Along with other costs, the cost for the wind tunnel tests needed for the development of an aircraft is steadily increasing. The present investigation is concerned with the effect of numerical aerodynamics and civil aircraft technology on the development of wind tunnels. Attention is given to requirements for the wind tunnel, investigative methods, measurement technology, models, and the relation between wind-tunnel experiments and theoretical methods.					
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DEVELOPMENT OF FUTURE COMMERCIAL  
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1. INTRODUCTION

The requirements for new technologies in civil aircraft design can be derived from the current uncertain profitability situation in civil aviation which is mainly expressed as

- the high procurement costs of modern fuel-efficient aircraft caused by sharply rising costs of development and manufacture, and
- long-term rise in fuel prices.

To the extent that we are dealing with aerodynamics, the testing of new technologies will be carried out in the foreseeable future solely through the agency of wind-tunnel measurements. For example, comparisons of performance of the latest wing designs between the partners in Airbus Industries (AI) were only carried out using experimental results. Advanced computational methods are adapted to wind-tunnel tests and the findings stretch back over some decades. While it is true that theoretical computational methods have been employed with great success in design, wing optimization (along with corrections to the wind-tunnel model), and in estimating the Reynolds number influence, nevertheless validation is only by wind-tunnel testing. However, if in the development of new aircraft, performance predictions are determinative and if these are passed along as guarantees to potential customers, then the greatest

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demands are placed in the area of wind-tunnel technology so as to minimize the risk in this area; the development costs for an aircraft today are in the order of magnitude of 5 billion DM.

Figure 1 shows the dramatic rise in the cost of aircraft construction over recent decades. While the Wright brothers worked using about 50 hours in wind tunnels, today, in the case of large-scale aircraft it is between 18 000 hrs (A310) and 35 000 hrs (B767), for which at least US \$1500 per wind-tunnel hour has to be expended in Europe. /2/

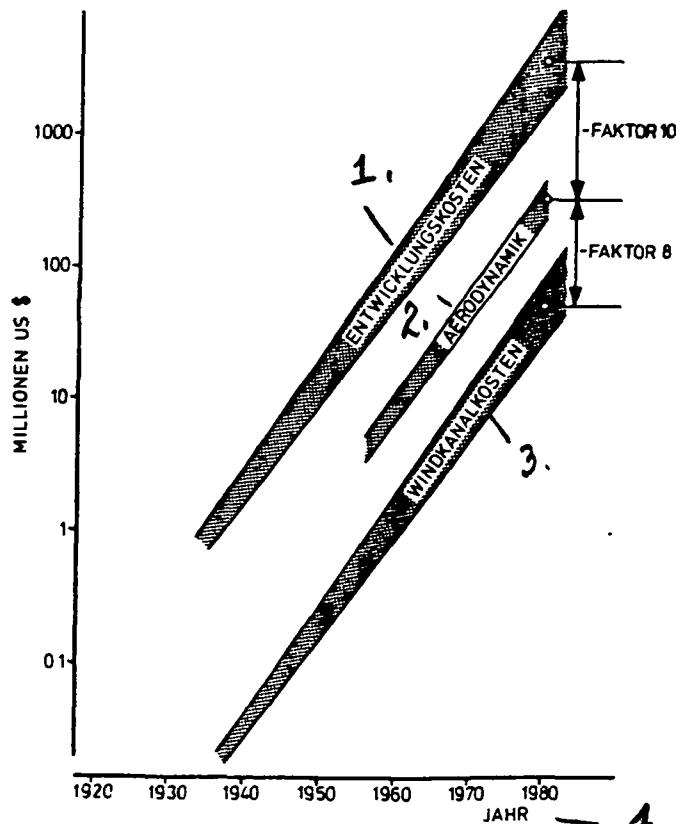


Figure 1: Cost increase in aircraft construction

1. development costs
2. aerodynamics
3. wind tunnel costs
4. year

Looking at these numbers and at the advanced technological standard to be set, future wind-tunnel development must be more precisely investigated.

In Figure 2 are roughly outlined the manifold specialist areas which have an influence on wind tunnel design. In this investigation, only the effects of numerical aerodynamics and civil aircraft technology on the future development of wind tunnels are discussed. Generally, reports are made on the specifications for

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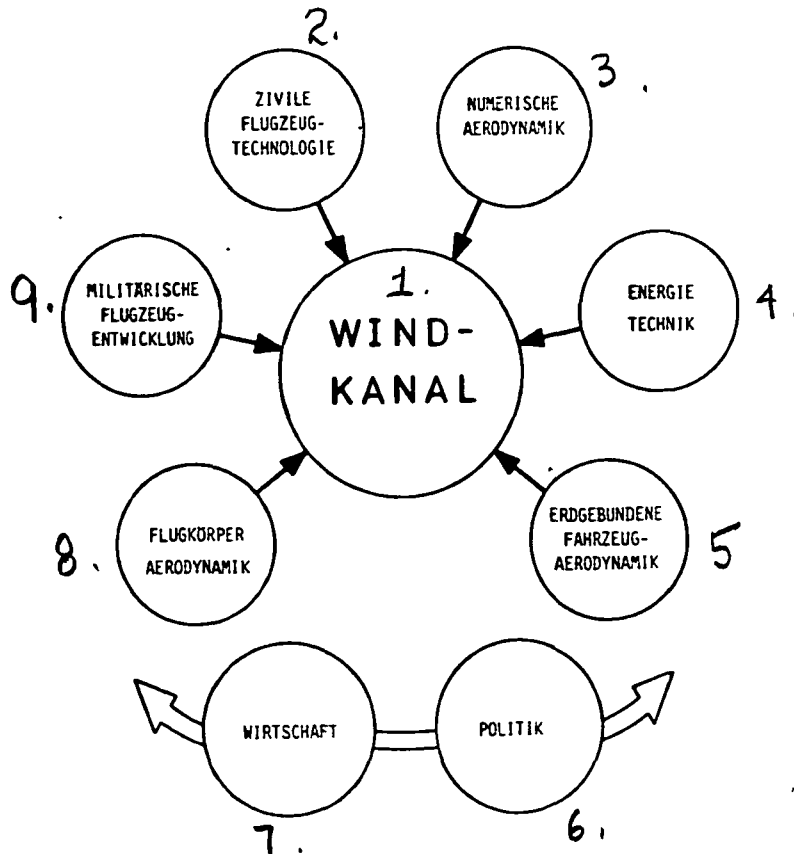


Figure 2: Influences on wind tunnel development

- |                                     |                                  |
|-------------------------------------|----------------------------------|
| 1. wind tunnel                      | 6. policy                        |
| 2. civil aircraft technology        | 7. economics                     |
| 3. numerical aerodynamics           | 8. fuselage aerodynamics         |
| 4. energy technology                | 9. military aircraft development |
| 5. terrestrial vehicle aerodynamics |                                  |

wind tunnels, the investigatory methods, the required measurement technology, as well as the necessary steps in the construction of wind tunnel models. Finally, a prospect is given on possible linkage of experimental investigations in the wind tunnel and theoretical computer processes.

2. THE CARRYING OUT OF WIND TUNNEL MEASUREMENTS

/4/

Before we explain the effects on the wind tunnel of the newer technologies in aerodynamics, it seems useful first to analyze current practice in industrial wind tunnel operation. In the interest of better understanding, we first consider the development history using an airfoil wing as an example. Figure 3.

In the development cycle the central position is occupied by concept/model construction/experiment, because the findings gained with this provide the bases for the nominal/actual comparison, and thereby for the competitiveness of the product.

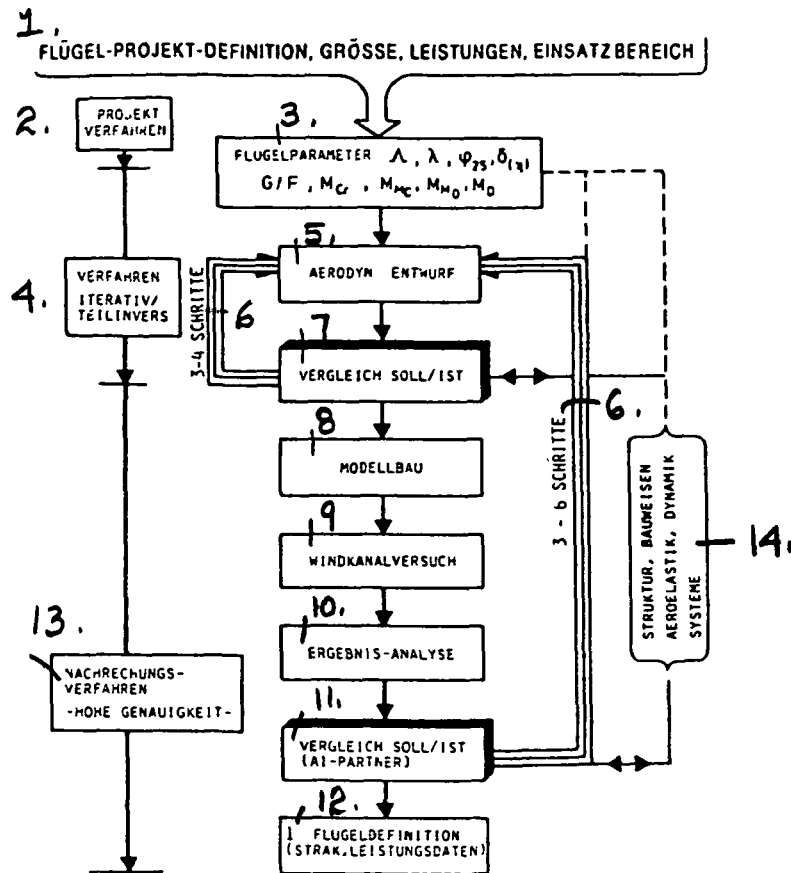


Figure 3: Developmental history using an airfoil wing as an example.

1. wing project definition, size, performance specs, range of usage
2. project procedure
3. wing parameters
4. procedure: iterative partial inversion
5. aerodynamic layout
6. steps
7. nominal/actual comparison
8. model construction
9. wind tunnel testing
10. results analysis
11. nominal/actual comparison (with AI partners)



12. 1. wing definition (smoothed outline, performance data)
13. recomputation procedure-increase accuracy
14. structure, types of construction, aeroelasticity, systems dynamics

Figure 4 is a somewhat more detailed explanation of the relationship between model construction and experiment. It shows that there is a considerable number of work steps to be traversed between the concept and the testing; here at the same time there is also exhibited the restricted flexibility of this kind of system.

/5/

In addition, the time history is dependent on the model dimensions (appropriate wind tunnel size). As an example, it can be mentioned that about 4 months elapse between model design and transport in the case of a typical transport aircraft model for transsonic measurements at a scale of 1:38 (  $\hat{\approx}$  total span of 1.2m), while for the same model in a 1:9.5 scale (  $\hat{\approx}$  total span of 4.5m) about 9 months must be committed. Similar factors also apply to the planning and preparation phases for the experimental aerodynamics and the wind tunnel. Therefore, the decisive criterion in the schedule planning is the construction of the model. If one takes these data as a basis, it becomes understandable then as to why the resources commitment is very high in experimental aerodynamics.

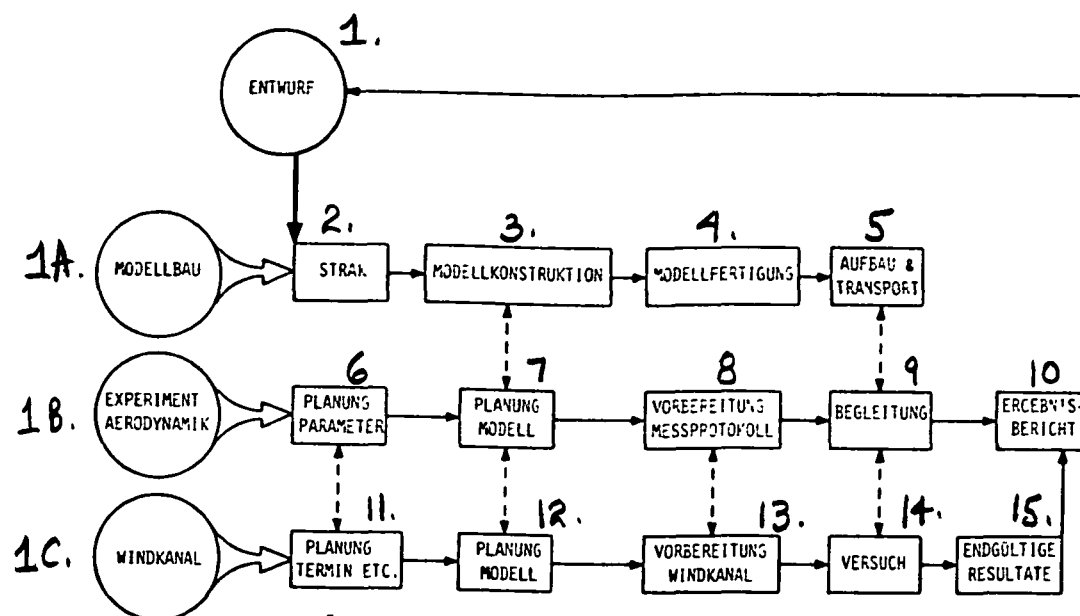


Figure 4: Relationship between model construction and experiment

1. layout
- 1A. model construction
- 1B. aerodynamic experiment
- 1C. wind tunnel
2. smoothed outline
3. model design
4. model fabrication
5. mounting and transport
6. planned parameters
7. planned model
8. preparation of the measurement protocol
9. accessories
10. report of results
11. planned schedule etc.
12. planned model
13. wind tunnel preparations
14. testing
15. final results

Figure 5 shows an example here for the /6/ experimental expenditures in a research program in which the average cost fraction for model design, model fabrication, measurement costs and test personnel amount to about 60% of the total resources.

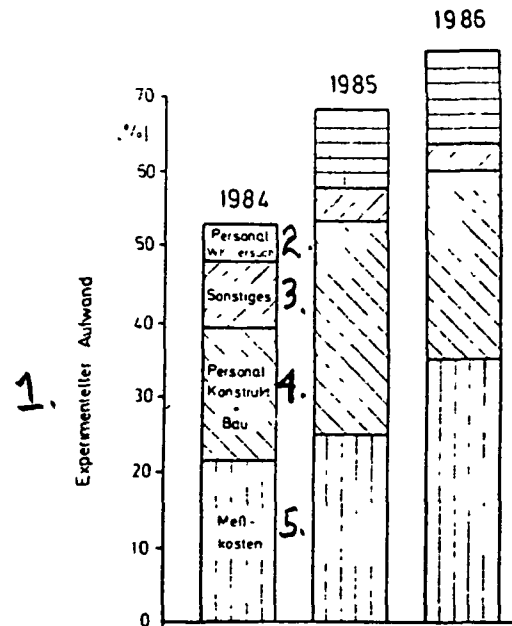


Figure 5: Outlays for model design, wind tunnel model construction and measurement costs

1. experimental outlay
2. personnel for wind tunnel test
3. miscellaneous
4. personnel for design and construction
5. measurement costs

The increase in the measurement cost fraction in recent years of this prediction is associated with the fact that measurements in large wind tunnels with correspondingly large models will become necessary in order to guarantee the results. This wind tunnel and model strategy is also portrayed in schematic form in the next figure, Figure 6, and likewise it can be brought to bear for research and development programs, in which, in the latter case, even more tunnels can be employed.

Here again it becomes clear that small models and tunnels represent the basis for the development work and that large model measurements are very expensive and mostly constitute the close of the research phase and/or project work. /7/

In the introduction, the considerable increase in wind-tunnel hours in aircraft developments is alluded to, without, however, going further into the annual wind tunnel load equalization. Therefore, we must definitely discuss here the question as to whether the effectiveness of wind tunnels has been correspondingly expanded.

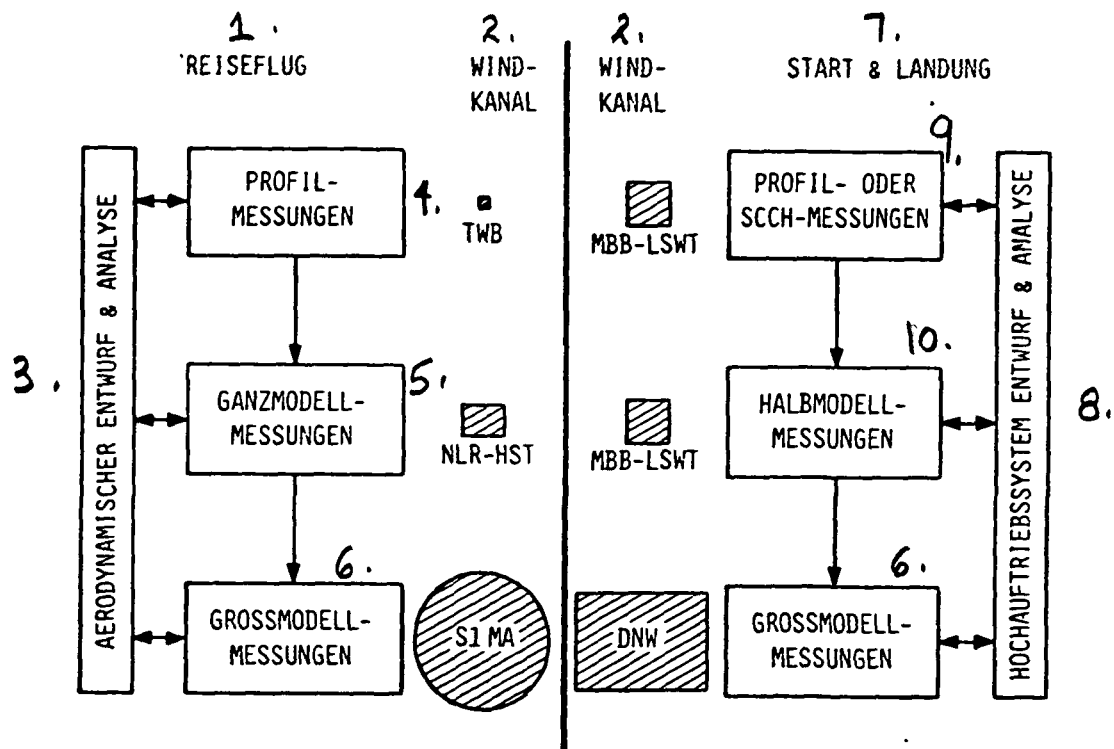


Figure 6: Model strategy for research programs

1. cruise
2. wind tunnel
3. aerodynamic layout and analysis
4. profile measurements
5. whole model measurements
6. large model measurements
7. takeoff and landing
8. high lift system layout and analysis
9. profile or SCCH measurements
10. half-model measurements

First of all, it should be recalled that the require- /8/  
ment for wind tunnel hours can vary widely over the life of  
one or more development phases. As an example, there is  
presented in Figure 7 the number of transsonic wind tunnel  
hours over almost a decade in the generally used wind  
tunnels. A differentiation is made between ZKP financed  
research tasks and other projects and special programs.

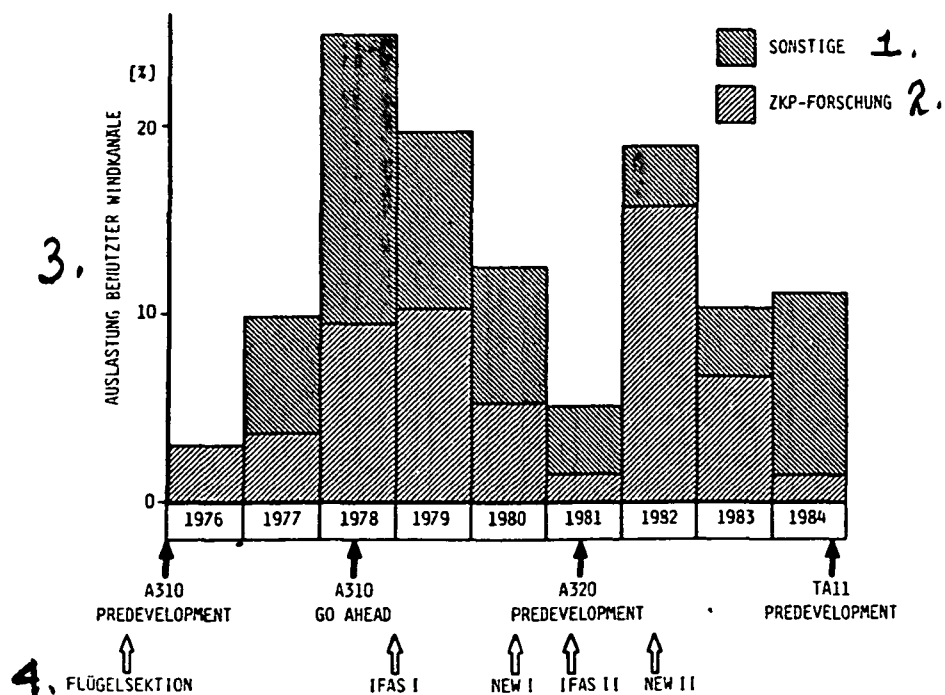


Figure 7: Example of the distribution of transsonic  
measurements within a decade

1. other (research)
2. ZKP research
3. load on wind tunnels used (%)
4. wing section

In contrast to the transsonic, where between minimum and maximum wind tunnel usage the factor of 5 to 6 can be employed, for the low speed range this is considerably lower--about a factor of 2. The number of wind tunnel days for the low speed range are about three or four times as

high as in the transsonic, however the total costs increase only by a factor of about 1.5.

Now the wind tunnel days cited here are not in themselves an index of the data density aimed at. In order also to give more precise indications there are plotted in Figure 8, as an example, for the MBB subsonic wind tunnel, the measurement series within the compressor operating time, again over a decade.

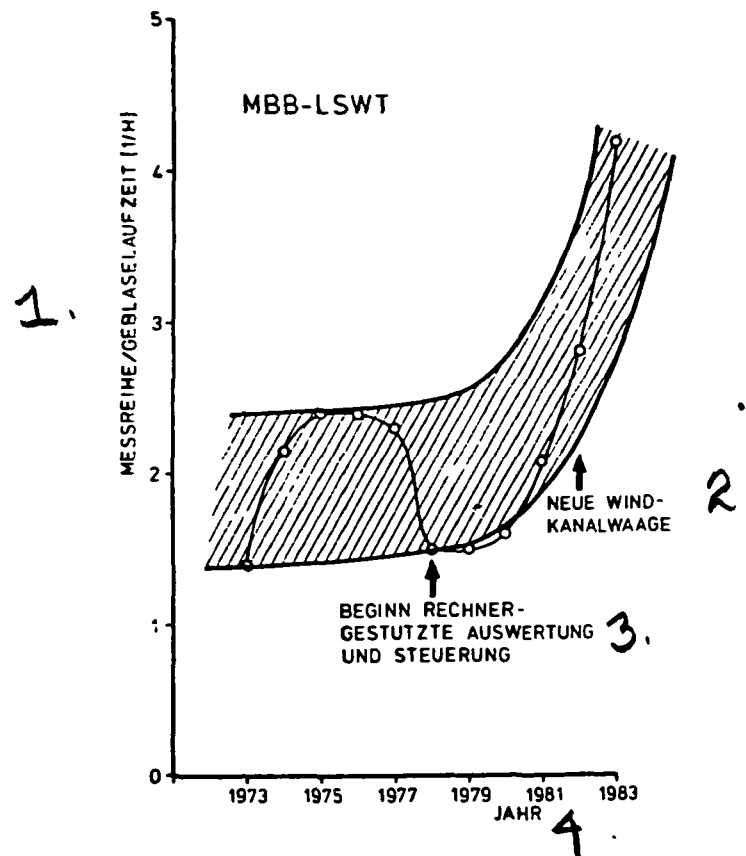


Figure 8: Influence of peripherals improvement on wind tunnel effectivity

1. measurement series/compressor operating time (1/hr)
2. new wind tunnel balance
3. start of computer-assisted evaluation and control
4. year

There are longer or shorter measurement series based on the partially very different specifications, and therefore a

relatively broad dispersion range. Nevertheless, the influence can clearly be recognized of the computer-supported evaluation and the installation of a new, faster wind tunnel balance, so that on the average today 4 measurement runs per hour of compressor operating time can be achieved. Measurements with engine simulation using TPS (Turbo Powered Simulator) should be set up for a longer period, by a factor of 2. While here the measurement runs are from the outset of shorter duration, the number of data to be measured is sharply increased.

Improvements, especially in this area, are /10/ provided by modern pressure measurement systems which permit shorter measurement times than the ordinary Scanivalve by a factor of around ten. Beyond this, greater improvements are to be achieved by more extensive control of the tunnel and the model (even with TPS). However, the larger data yield per tunnel hour achieved heretofore has not been fully utilized. After all, the number of data has increased over the course of a decade by a factor of 10 (1). The important points of comment on this are summarized in Figure 9 and do show that there is available a considerable unexploited data potential, and/or measurement times that could be better employed.

Improvements must be striven for in the field of measurement philosophy, based on more stringently focussed measurement programs using revised computer-based preparatory work. Optimization projects, e.g. in the high-lift range must be strengthened with appropriate optimization strategies. Finally, the mind-set needs to be basically reconsidered which says "right now we will possibly call on this unused data at some future time". A reduced flood of data, given the same available time for evaluation, promises higher effectiveness and allows more time to study the flow physics more intensively.



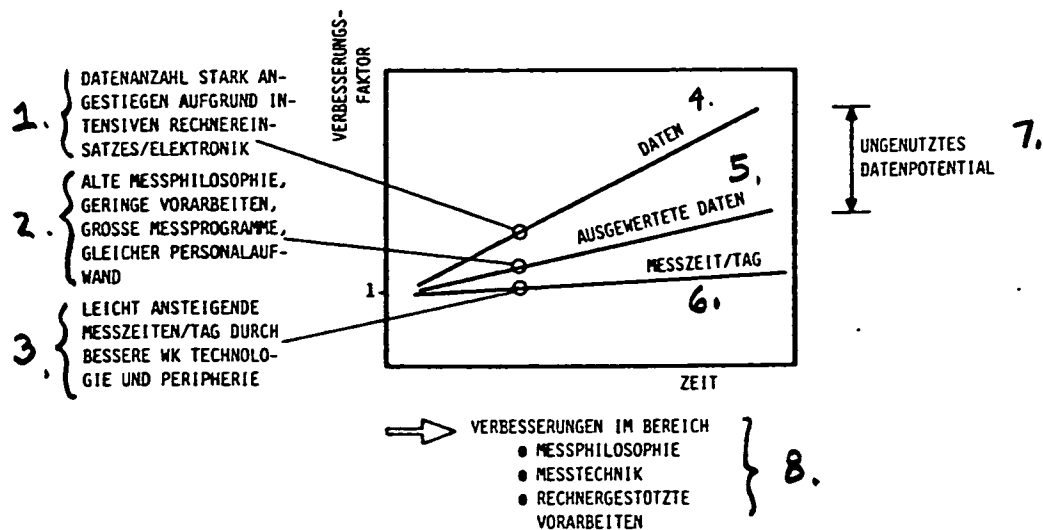


Figure 9 Amounts of data collected and their evaluation

- |  |  |
|--|--|
| 1. number of data sharply increased due to intensive use of computers and electronics          | 2. old measurement philosophy of limited preparation, large measurement programs and expenditures for personnel  |
| 3. slowly rising measurement time in days due to better wind tunnel technology and peripherals | 4. data  |
| 5. evaluated data  | 6. measurement time in days  |
| 7. unused potential  | 8. improvements in the area of <ul style="list-style-type: none"> <li>o measurement philosophy</li> <li>o measurement techniques</li> <li>o computer-assisted preparation</li> </ul> |

Further, efforts must be made in the field of measurement technique to put new methods into uses, including the area of engineering measurements, so that it would be possible to measure, using precision measurement procedures, those flow parameters which heretofore have only

been produced by means of data intensive tests. Here are particularly to be mentioned the laser-doppler-anemometer and the laser interferometer for determination of wall tangential stress. In the future, versatile methods for establishing transition and for recognition of the shock-transition position will be indispensable as well.

A complete discussion of the advantages of the employment of computers in experimental aerodynamics is in the last section.

A significant factor in assessing the effectivity of wind tunnel measurements is the quality and the standard of the wind tunnel model. Figure 10 shows how strongly the design of the model influences the overall usage time of the wind tunnel.

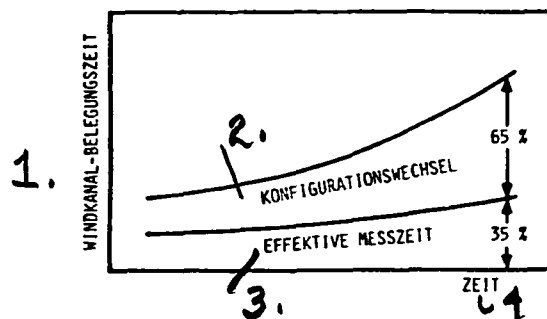


Figure 10: Proportions of wind tunnel operation and non-operating times in a single measurement job

1. wind tunnel usage time
2. configuration change
3. effective measurement time
4. time

Here it is schematically shown that the fraction of the configuration change (i.e. the wind tunnel does not change) is at present about 65%. Deviations from this exist depending on the measurement job, however on the average one can assume this value both for the subsonic and transsonic wind tunnels. We must try to get more innovation here both

in the design of models and in their fabrication, in order to achieve longer effective measuring times. Details on the requirements are treated in the next section.

### 3. WIND TUNNEL TECHNOLOGY FOR FUTURE AIRCRAFT AERODYNAMICS

Mid-term and long-term research planning embrace a series of aerodynamic technologies which, on the one hand, promise considerable increases in performance, but which, on the other hand demand increased development expenditures with respect to material and personnel. As already discussed, experimental aerodynamics will also play a support role in the future. Therefore, the technical situation, and the financial implications as well, need to be newly reconsidered in all their aspects as they pertain to future wind tunnel investigations.

#### 3.1 Future Technologies in Aerodynamics

In order better to understand the requirements developed in the next section, we will very briefly here go into the important aerodynamic research subjects for the next few years. According to priorities in their treatment and in their introduction into future commercial aircraft, the following research main effort points can be named; they are also sketched out in Figure 11 and are treated in detail in (2).

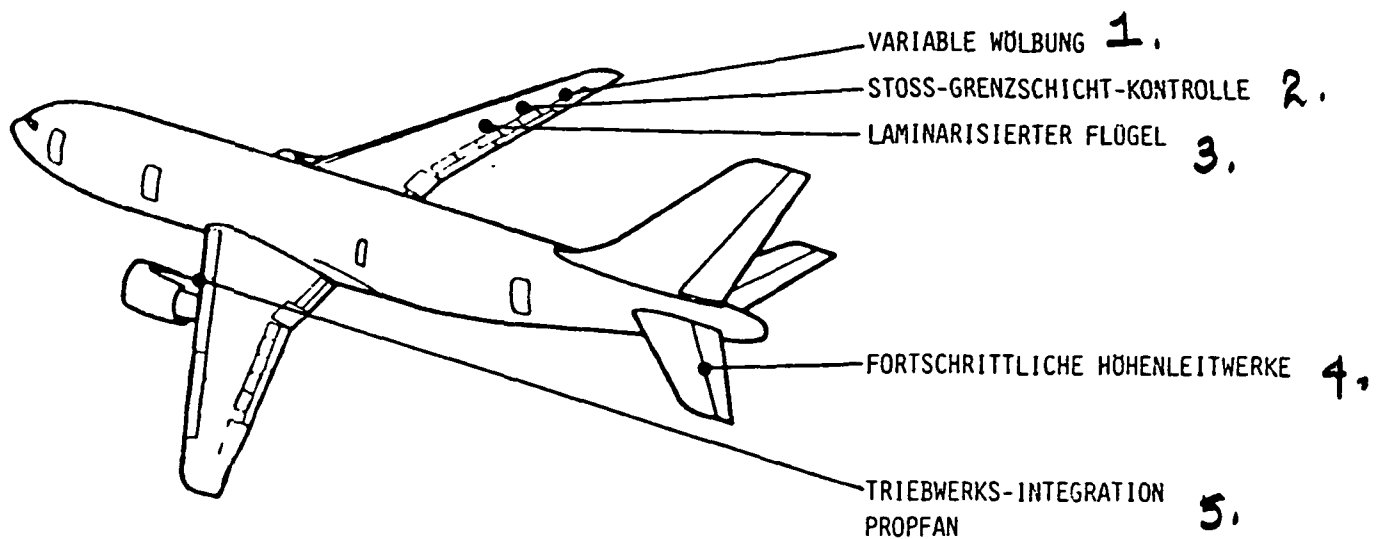


Figure 11: Future aerodynamic technologies

1. variable camber
2. shock boundary layer control
3. laminarized wing
4. advanced horizontal stabilizers
5. engine integration  
propfan

Variable camber is an aerodynamic concept in /13/ which the flap system already present on the lifting wing is so employed that it makes possible throughout the entire flight regime--takeoff, cruise, landing--the best possible adjustment of the geometry to the existing flight condition--lift coefficient and mach number--by appropriate setting of angle and/or run-out. Variable camber can take place either in the span or the chord direction. Thereby, both the lift/drag ratio and buffet control is possible, together with control over gust and maneuvering loads. It is conceivable that this concept can be introduced in the mid-term, i.e. in the next generation of Airbus Industrie aircraft.

In the case of supercritical profile flow, active and passive shock boundary layer control can take place by means of slots or perforated strips in the shock zone. The local suction applied to the boundary layer delays the shock-induced onset of flow separation and thereby markedly improves the aerodynamic properties of the profile. But even without suction, if a double slot (in front of and behind the shock) or a perforated strip with a chamber located beneath, is used, improvements in aerodynamic profile characteristics can be perceived. Heretofore these findings have been valid only for two-dimensional flow. Only with proof of this promising passive control of shock boundary layer interaction on the three-dimensional wing can there be a prognosis about introducing it in aircraft mass production.

The laminarized wing is a concept, long recognized and practiced in sailplanes, which now, for example, is also being prepared for employment in commercial aircraft. Laminar flow can either be stabilized through selection of pressure distribution (natural laminarity-NLF) or can be positively influenced by skin suction (laminar flow control-LFC). A hybrid process has been investigated in which only the leading edge area has suction and downstream large wing areas are laminar (HLFC). In general, in the concept, parameters like wing sweepback and leading edge radius are to be taken into account, without, however, giving up the advantages of supercritical profiling. A further important parameter is the surface quality of the wing. In Europe also, it will require considerable research effort to bring this technology to maturity for commercial aircraft.

The two last subjects engine integration and /14/  
advanced horizontal stabilizers are closely linked to wing development and are mentioned here on account of their great

significance. Interferences between nacelle, jet and inlet flows and the wing must be considered in the concepts both for variable camber and for the laminar wing, and this should be experimentally tested. In integrating propfans, particular problems can be expected with respect to the engine-air frame interference. The concept of horizontal stabilizers which are matched to the downwash is strongly impacted by the rear fuselage configuration, but in addition the variable downwash conditions must be considered in the variable solution. For both these subjects there is an abundance of preparatory work at hand, so one can count on continual improvements in future aircraft.

### 3.2 Specifications for the Wind Tunnel and Applicability of Existing and Planned Facilities

Based on the above described new technologies in aerodynamics, we discuss more precisely in the following the specifications for the wind tunnel and take a critical look at the currently existing and/or planned European facilities from the standpoint of industry, using the measurement values, the simulation parameters, the measurement system and the measurement methods.

With respect to the measurement values, particularly the aerodynamic coefficients, no basic modifications can be expected based on the new technologies. The requirements which should be here specified for the findings of the advanced computations produced by the wind tunnel can be projected as follows according to the pre-development, definition and project phases, respectively, i.e. final assurance of the findings as a basis for guarantees:

Pre-development	$C_W$	3%
Definition	$C_W$	2%
Project	$C_W$	0.5%

These values apply for cruising flight and consequently signify for the project phase an accuracy of about 1.5 drag

counts ( $C_W = 0.00015$ ).

These specifications can already be met even today /15/ with a great deal of care and the associated large financial outlay. As an example here, need only be mentioned the S1 wind tunnel of ONERA's at Modane where computations can be carried out with the following accuracies:

$$C_W = \pm 0.00011$$

$$C_A = \pm 0.0035$$

$$\Delta\alpha = \pm 0.015^\circ$$

In addition, as has just been shown, even the reproduceability of the measurement values between measurement runs at differing times and with intervening redesign of the model can still lie within the above mentioned limits. Here additional improvements must be demanded in other transsonic wind tunnels so that, even in reduction of the reference measurements, this level of certainty can be attained in the evaluation of results.

In the high lift range, similar specifications are set, and here in particular the DNW should be mentioned, where accuracies, and also long-term reproduceability in drag coefficients of smaller than 0.5% have been measured.

Here it must be once again pointed out that the values for accuracy and reproduceability given above do not apply to a single system component but rather embrace the overall measurement technique, flow parameters, model geometry, model suspension etc.

Among the simulation parameters, the Reynold number must be here particularly called out, which is of great influence for all the technologies named. In order once again to indicate the importance of the Reynold number in aircraft development, there is sketched in Figure 12 the long road, beset with uncertainty, which stretches from wind tunnel measurements to the advanced computations on the full scale production. The wind tunnel results are usually first

corrected appropriately for the wall inteferences in order subsequently to discover an adjustment based on specific wind tunnel drags (e.g. transition strips, flow-through nacelles etc.)

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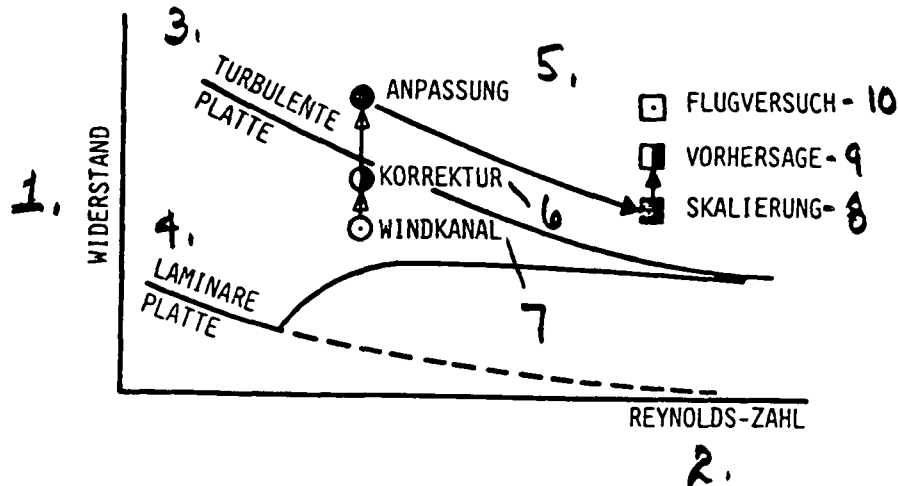


Figure 12: Prediction method from wind tunnel finding to full-scale model

1. drag
2. Reynolds number
3. turbulent plateau
4. laminar plateau
5. adjustment
6. correction
7. wind tunnel
8. scaling
9. prediction
10. flight test

In extrapolating to flight Reynold numbers, parasitic and trim drags, engine installations and differences between model and full scale design all have to be considered.

With wind tunnel tests with the accuracy mentioned above and with carefully prepared flight testing, it is



possible to determine the difference between flight testing and the prediction at  $\Delta C_W \leq 1\%$ . This value already lies within the accuracy of the flight tests. Unfortunately, these good prediction results cannot always be attained. (1).

The Reynolds number, however, does not just play an important role in the advanced computation, but the quality of the concept of a wing is already affected by Reynolds number effects. In order to minimize the risk of flow separation, wing concepts are now layed out such that, within the existing Reynolds number simulation range of European wind tunnels, no separating flow areas occur.

As is known, in wind tunnel tests, the Reynold number is taken into account with boundary layer control using transition fixing. These methods for fixing the laminar-turbulent transition are weighted with great uncertainty, since a solid basis in physics has not been heretofore available.

However, even for the next few years, concept philosophies must require that clearly defined laminar-turbulent zones are present on the wing in order also in the future to maintain the prediction accuracy previously attained. If one now considers the new aerodynamic technologies discussed above, particularly the program for variable camber which provides for wind tunnel models with remotely controlled flap systems, then the requirement for flexible methods of transition fixing becomes specially urgent, even including variable recognition of the reversal (3).

/17/

In the long-term, improvements in the field of Reynolds number simulation in the area of wind tunnel concepts can be expected with the planning of the cryogenic ETW facility (European Transsonic Wind Tunnel). Details on this tunnel, including the diverse new test capabilities will not be

discussed here but they appear in (4) and (5). In Figure 13 is plotted the Reynold number simulation range of the ETW compared with existing European tunnels and the flight Reynolds numbers of the Airbus family. Here it becomes clear what possibilities and advantages the industry looks forward to from this kind of a facility.

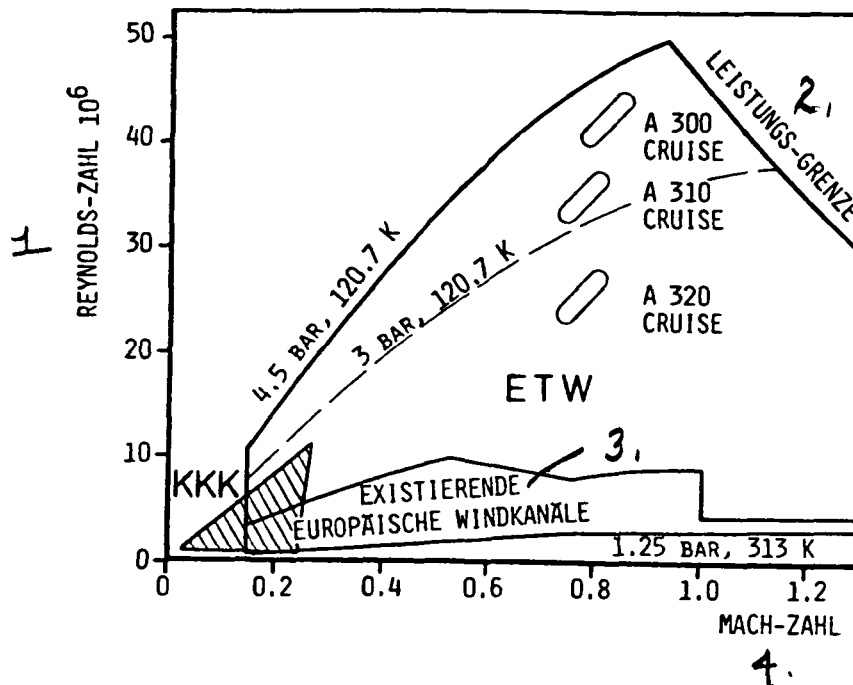


Figure 13: Reynolds number range of the ETW and KKK

1. Reynolds number
2. performance limit
3. existing European wind tunnels
4. mach number

The ETW will be required in well-nigh all phases of development. Besides the direct aircraft development, it will be employed in order to generate detailed understandings of the physics of flow, ultimately to achieve improvement in the conceptual process. In the project phase, measurement results at high Reynolds numbers are especially valuable in order to make the prediction method, already exhaustively treated above, considerably less risky and to strengthen the associated guarantees. But the ETW will be able to produce significant contributions to the further development of already existing aircraft designs as well. In Figure 14 is outlined the timeline for current ETW programs and of the new and further developments in the Airbus aircraft family. /18/

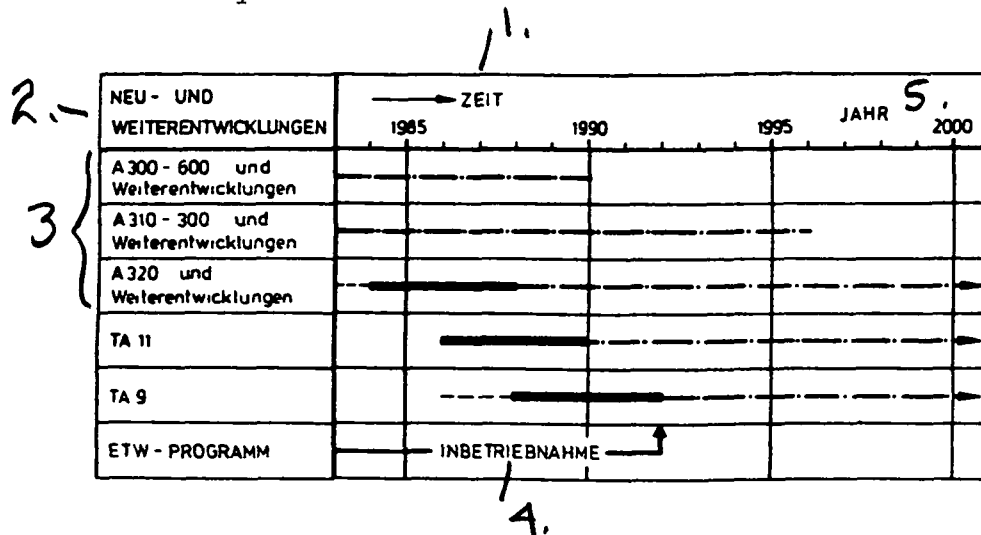


Figure 14: New and further developments in the Airbus program

1. time
2. new and further developments
3. (aircraft designated) and further developments
4. entry into service
5. year

Of course the entry into service of the tunnel will not be immediately linked to productive industry measurements. Rather one must start with a transition phase during which confidence in the interpretation of data is gained by comparisons between conventional methods in industry and the cryogenic measurement results. The urgency for the employment of such a facility in Europe is emphasized on the one hand by the paucity of understanding on flow behaviour at flight Reynolds numbers of the new aerodynamic technologies such as variable camber and shock-boundary layer control, and on the other hand the competition in the USA is already making measurements with transport aircraft models in a similar, already existing facility.

In the subsonic regime, a useful facility will /19/ soon be available with the Cologne Cryotunnel (KKK), which is also of great interest to industry. After the calibration phase and the testing are ended, and when measurement technical materials (e.g. balances) and wind tunnel models are available, this tunnel offers a practical complement to the measurement series for whole or half model measurements using the possibility of varying the Reynolds number with constant mach number and dynamic pressure. Here become clear what kind of measurement tasks will accrue to the KKK and the fact that it represents no competition to the DNW. The Reynolds number regime for the KKK can also be seen in Figure 13 and is comparable to the RAE 5-meter or the ONERA F1 wind tunnels, both tunnels with variable static pressure up to 3 and 4 bar respectively.

The new technological requirement for "laminarized wings" will result in significant impacts on the flow characteristics in wind tunnels. The role of the wind tunnel in the beginning phase of a possible planning scenario for laminarization is shown in Figure 15.



In contrast to work in the USA where, with huge expenditures of time and money, whole measurement sections have been newly constructed just for fundamental research, existing wind tunnels have to be used, despite their disadvantages, on account of limited German and also European resources. In addition to this, flight testing must be carried out to a greater extent than heretofore in research and development projects.

For the wind tunnels, of which many already have a considerable number of operational years behind them, this subject of new technologies means detailed review and, if needed, a demand for improvement in flow characteristics. The turbulence level can serve as an example here; it exercises considerable influence on the laminar behaviour and/or the transition location. Figure 16. The analysis of wind tunnel data here shows a similar course to that of the computations of Michel (contained in (3)).

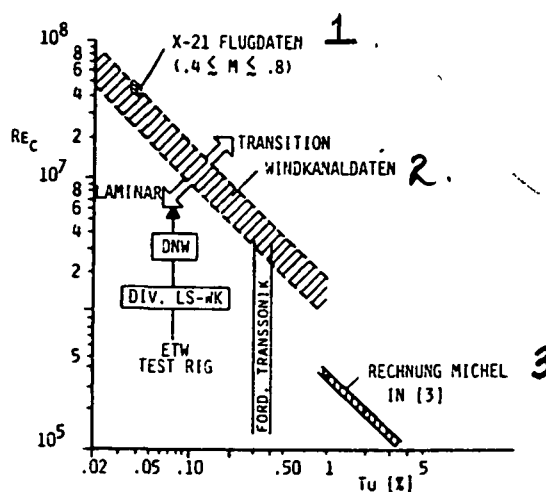


Figure 16: Influence of turbulence level on laminar behaviour

1. flight data
2. wind tunnel data
3. Michel computation in (3)

Also introduced into this diagram are the turbulence levels of some European tunnels for typical model configurations. These values should indicate that at least basic research and wind tunnel observations could be carried out with laminarized profiles and wings in some existing wind tunnels without all that great a need for modification.

Explicit influences of other parameters of the flow /21/ characteristics are less understood, however, there should be mentioned again the significance of pressure fluctuations among the dynamic magnitudes, see (6) and (8).

Certain specifications must be set also for test sections based alone on their dynamic flow characteristics. Perforated or slotted walls of transsonic test sections have a negative influence on the dynamic parameters and their effect must be determined in detail and suppressed or minimized depending on the measurement job. Wall interferences are generally of great interest not only in experiments on laminarization (behaviour of the undisturbed span-directional flow) but also for the other subjects as well. The well advanced concept of adaptive wind tunnel walls in (9) presents a solution; it promises very many improvements and/or expansions of the simulation regime in industrially employed transsonic tunnels. It is clear from Figure 14 that the ETW can only be put into service when advanced work is to be done in the new technologies, particularly the "laminarized wing". Thereby, the requirement also arises for the ETW to have non-porous adaptive walls.

If, finally, the diffuser area is critically considered, then in the case of laminarization experiments, it could become necessary to suppress the pressure fluctuations taking place upstream in the test section by means of a supersonic regime. Beyond this it must also be considered as to what method will be used to integrate

diffuser, suspension spindle etc. such that here also interferences on the test results can be kept as small as possible. Also, the interactions between suspension and the wind tunnel model make necessary relatively large corrections in the test values. A rudder suspension as shown in Figure 17 makes it possible to dispense with the geometric correction components, but it also considerably reduces interferences, e.g. with the tail/horizontal stabilizer area.

/22/

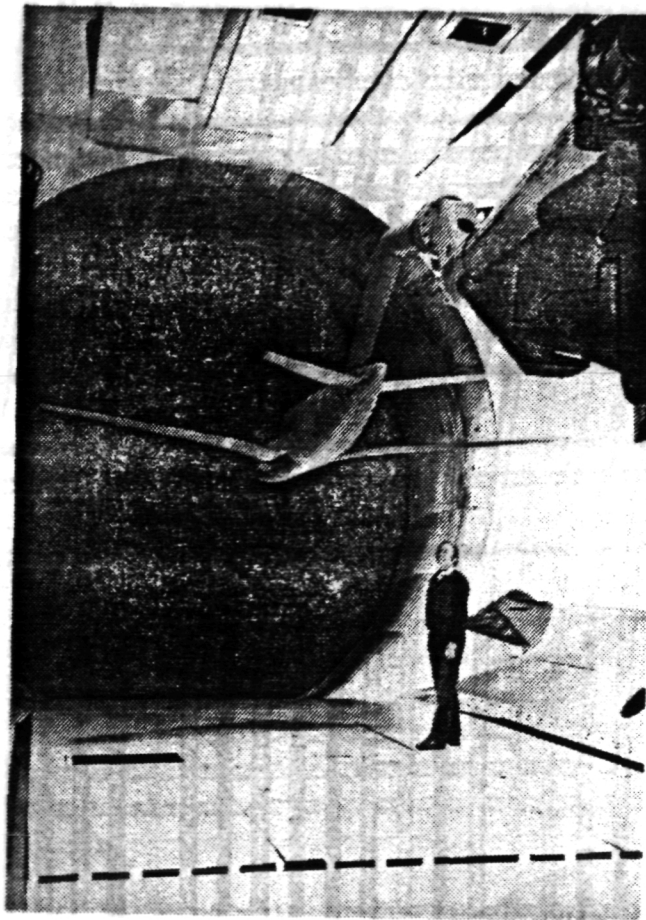


Figure 17: Rudder suspension of a large transport model  
(M1 : 9,5) in the SI transsonic tunnel



Finally we should address the question of measurement methods; here again more stringent specifications must be set from the side of industry. If one starts with the fact that about 80% of the potential of the supercritical wing has been exhausted, it becomes understood why any further work presupposes considerable detailed understandings about the flow processes. Other mid-term research subjects, as, for example, shock boundary layer control can only be brought to optimal maturity for application if details of the physics of the flow are known and understood. In the concept-to-flight cycle there is of course included the theory (see Figure 3) which is supposed to produce the appropriate computational and conceptual procedures, and for this, exact understanding of the flow physics and a data base is required. This applies to an especial degree to the boundary layer computations procedures, because normal industrial wind tunnel measurements produce for the most part only force magnitudes and pressure distributions.

In a quite general sense here, the boundary layer measurement technique must thus be usable for industrial measurements, so that precision investigations are possible, for example, on the large model in the DNW or the S1 (see Figure 17). Main points of application here would be the shock area, the trailing edges, and also interference areas like, e.g., the wing-fuselage transition. Of course, in these critical areas, non-intrusive processes are called for, so here great hope is placed in laser-doppler anemometry. But even just knowledge of the wall tangential stress distribution could produce useful indications about the flow physics. 23/

The measurement of pressure distributions always involves a quite considerable effort. Thus it frequently happens that the financial outlay alone, and right now scheduling considerations as well, do not allow for pressure

distribution measurement, even though from the technical standpoint important data remains concealed. The requirement for newer technology was already brought up 8 years ago in (5), but essentially no change occurred. In time, progress here can be expected from a piezoelectric foil which was used by Nitsche et al. in (3) for recognition of the boundary layer transition and which could also be used for steady-state measurements by extending the test technique.

### 3.3 Specifications for Wind Tunnel Model Construction

It was mentioned in the introduction what an important scheduling and cost position is occupied by wind tunnel model construction. Prototypical model series, the high cost component of model construction and the way in which model construction can influence the wind tunnel measurement costs have been described. A new link must be created in the model chain for the cryogenic wind tunnel KKK and for ETW. These models must mainly take into account two new test parameters: the low temperatures (down to  $110^{\circ}$  K) and the associated achievable high Reynolds number (up to about  $40 \times 10^6$ ). A significant, though not new factor in wind tunnel testing is the high dynamic pressure which is produced from a static pressure of about 4.5. Therefore, materials and design methods must be found which meet the specifications for strength, fatigue limit, low coefficient of expansion and high accuracy requirements (10).

Thereby, the surface quality is also of great influence for the subject "laminarized wing". Portrayed in Figure 18 is the permissible degree of roughness for the model as a function of the Reynolds number (here with  $c = 0.2\text{m}$ ). A value of about  $Ra \approx .25 \mu\text{m}$  was yielded for the ETW, compared with the current standard of wind tunnel models in use of about  $0.5 \mu\text{m}$ . /24/

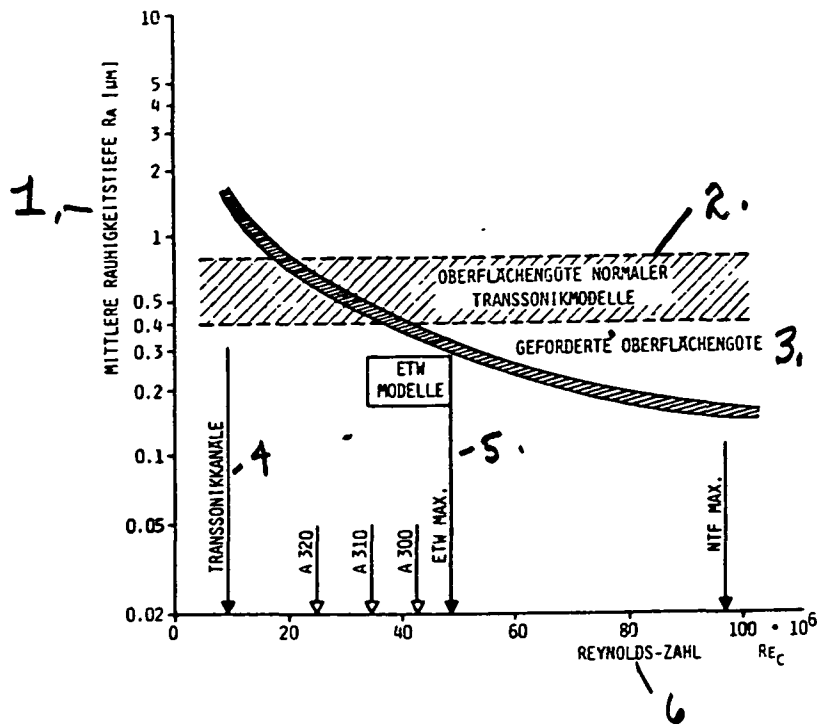


Figure 18: Roughness heights for cryogenic wind tunnel models (16)

1. average roughness profile depth
2. surface quality of normal transsonic models
3. required surface quality
4. transsonic tunnels
5. ETW models
6. Reynolds number

If it is also desired to try to measure wall tangential stresses with the laser interferometer (11), then roughness heights of about  $Ra \approx 0.1 \mu m$  must be specified. For one thing, analytical investigations have been carried out by Pfenniger (16) on the influence of surface ripple on the flow, and for another thing ripple has been measured on various aircraft (17), all, however, without having been able to determine any premature transition traceable to ripples. Pfenniger specified values around  $\lambda/\lambda \approx 0.001$  at  $Re_c \approx 40 \times 10^6$ , compared to the aircraft measurements of

$h/\lambda \approx 0.01$  at  $Re_c \approx 10 \times 10^5$  The usual values in current profile model construction are at  $h/\lambda = 0.001$  for Reynolds number up to about  $Re_c \approx 10 \times 10^6$  ( $h$  = height,  $\lambda$  = wave length).

For the technology of "variable camber", wind tunnel /25/ models must be especially planned which have the capability of controlling all, or even a part, of the moveable control surfaces using remote control adjustments. Basically the idea of remote control adjustments is not new and has already been put into practice with easily accessible components and for the simpler kinematics, e.g. with horizontal stabilizers. But in the future it will also be required to control Fowler flaps, for example, without affecting the other functions in the wing such as pressure distributions, TPS installations etc. This great challenge for model design and fabrication is not just limited to the layout of the adjustment simulation, of the adjustment linkage and to the general problem of installation in the relatively thin wing, but also the accuracy, reproducibility and monitoring of the adjustment is of the greatest importance. These kinds of complex adjustments can at the moment only be realized on a large half-model (e.g. scale M1 : 5.4 corresponds to a half-span of  $b/2 \sim 4m$ ). For whole models, in, e.g. the DNW, one can conceive of a simple adjustment with two fixed end limits.

For more long term planning for the research subject "variable camber", remotely controlled adjustment, based on the multitude of test parameters, is needed to keep the cost framework for wind tunnel measurements within reasonable limits.

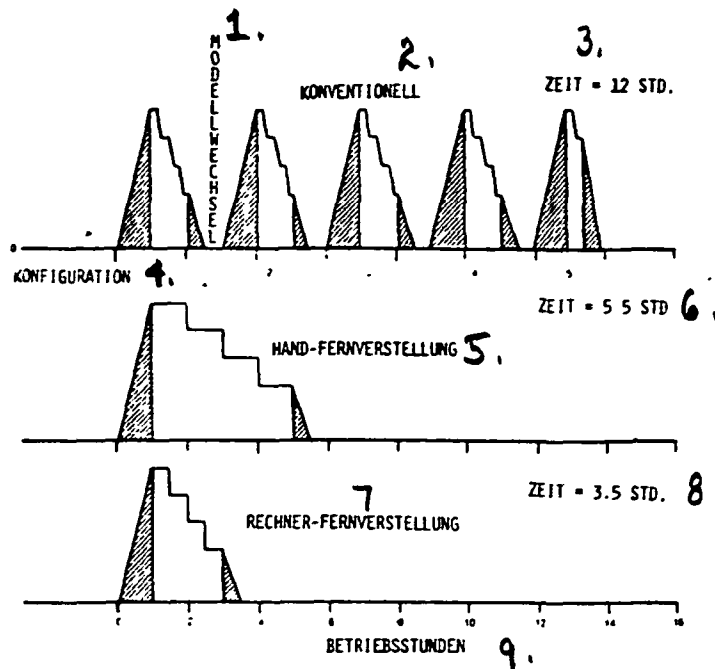


Figure 19: Time savings with wind tunnel models having  
remotely controlled setting (12)

1. model changeout
2. conventional
3. time = 12 hrs
4. configuration
5. manual remote setting
6. time = 5.5 hrs
7. computer controlled remote setting
8. time = 3.5 hrs
9. operating hours

In the final phase of the project, one can even conceive of carrying out in the wind tunnel a fully-automatic adaptation of the optimum camber to the flight condition. In the long term of course the advantage of remotely controlled adjustments can also be foreseen for other research jobs, since wind tunnel usage times will be dramatically shortened (see Figure 10) and/or the effective test time can be increased. In Figure 19, using the Space Shuttle as an example, with still fairly simple flap

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kinematics, there is shown the time savings at different degrees of automation of the remote control. According to this, the gain can be between 50% and 70% compared to conventional model employment.

4. WIND TUNNEL AND COMPUTER--THEIR COMMON FUTURE

Since the well-known and often-cited article "Computer vs Wind Tunnel", many speculations, and unfortunately also erroneous interpretations have been set in motion concerning the employment of the computer with the wind tunnel. It is only certain that even ten years ago it had been realized that here the work was not adversarial but that wind tunnels and computers faced a common future. Therefore, in the following will be discussed, from the industrial side, the interplay of computer and wind tunnel, with particular attention to the test technology.

The important role of the computer in aircraft design has already been shown in Figure 3 and is discussed in detail in (14) and (15). It can be assumed from this that in the near future details of the flow will be numerically investigated wherever the required experience and reliability are present. On the other hand, however, the theoretical procedures also require flow physics underpinning and a data base, in particular from the area of applied aerodynamics (e.g. engine-airframe interference or wing-fuselage transition area). It is therefore foreseeable in the future that the coupling between theory/concept/wind tunnel shown in Figure 20 can be created. The number of wind tunnel hours required, also shown in Figure 20, will however in this way only be insignificantly changed; this is because the detailed measurements needed for the physics of flow will be more time-intensive than normal performance measurements. Only the result of the numerical experiments can provide a certain removal of this load.

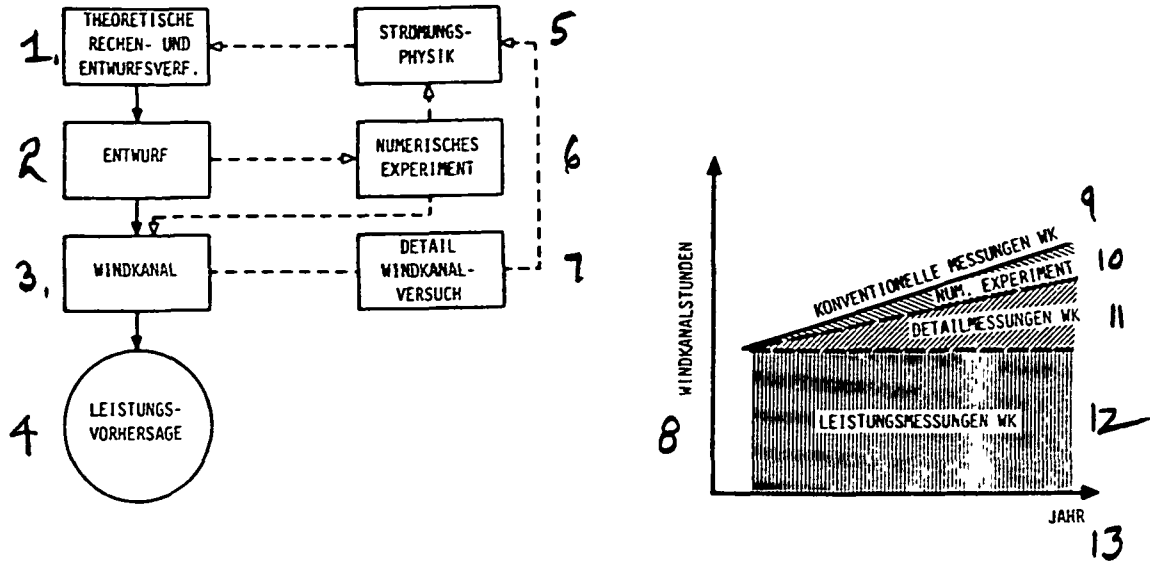


Figure 20: Coupling of Wind Tunnel and Computer

1. theoretical computer and conceptual procedure
2. concept
3. wind tunnel
4. performance prediction
5. flow physics
6. numerical experiment
7. detailed wind tunnel test
8. wind tunnel hours
9. conventional measurements- wind tunnel
10. numerical experiments
11. detailed measurements-wind tunnel
12. performance measurements-wind tunnel
13. year

In Figure 21 the average expenditures for typical completed and planned industrial research show the increasing wind tunnel costs with moderate increased computer costs. Particularly dramatic is the difference of the costs between computer and wind tunnel in the case of the advanced development programs, in which to a great degree the performance data in the wind tunnel must have priority.

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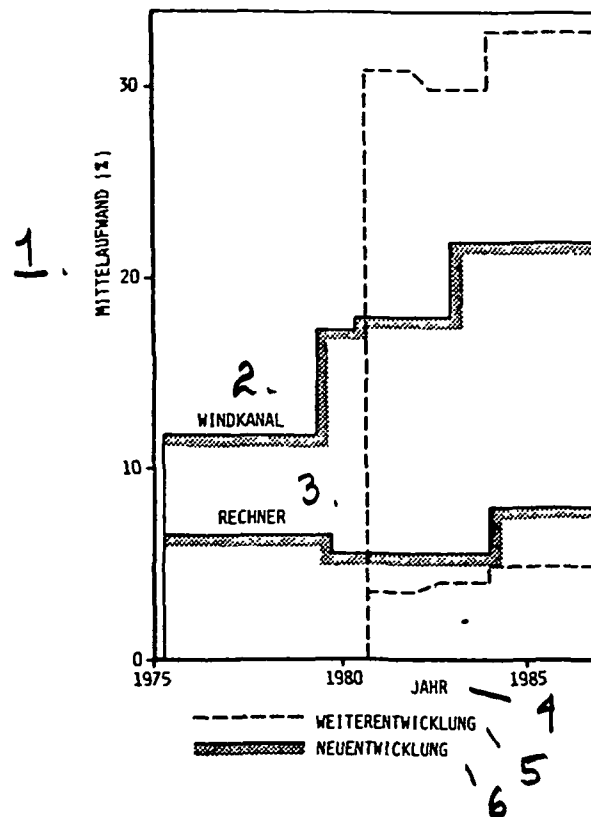


Figure 21: Mean expenditures for computer and wind tunnel  
for typical industrial research tasks

1. mean expenditure (%)
2. wind tunnel
3. computer
4. year
5. advanced development
6. new development

The employment of the computer in direct connection with the wind tunnel, as already described above, showed considerable influence on the data density.

Summarized in Figure 22 are further possible thoughts on integration and procedure from wind tunnel and model control/monitoring to optimization in the wind tunnel in connection with theoretical concept data. This last phase, of particular interest in the high lift regime or in the "variable camber" area, assumes a remotely controllable model.

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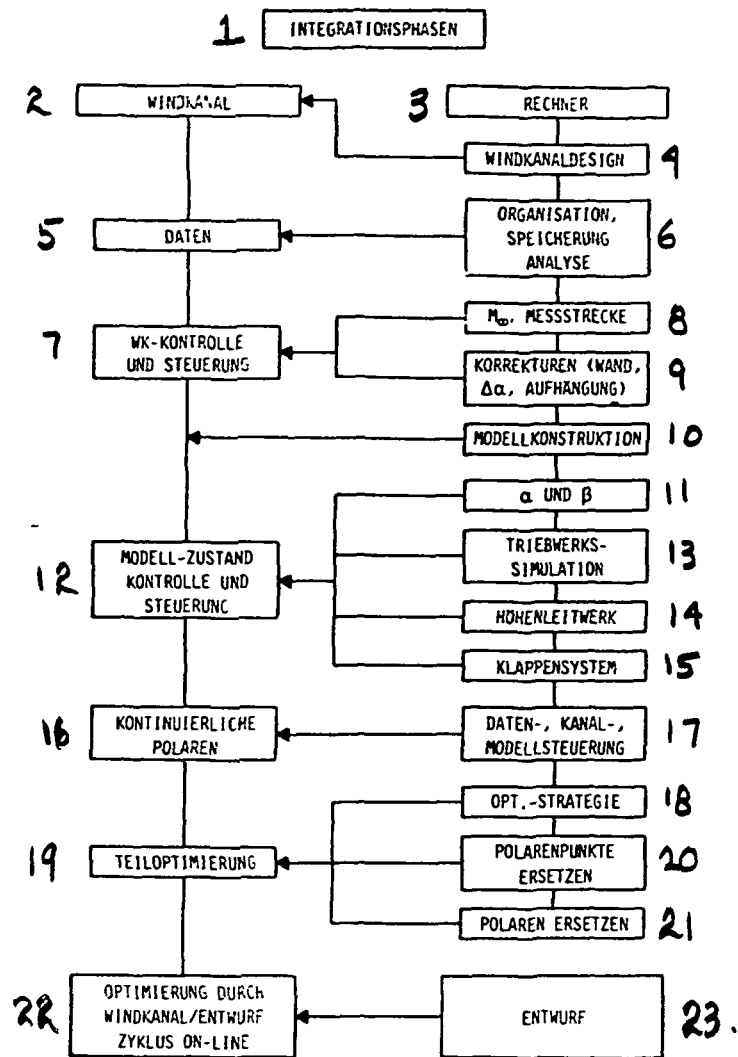


Figure 22: Direct employment of the computer on the wind tunnel  
(NOTE: TERMS FOR FIGURE 22 ON NEXT PAGE)

- |  |  |
|--|--|
| 1. integration phases                                    | 11. $\alpha$ and $\beta$                 |
| 2. wind tunnel   | 12. model status, monitoring and control |
| 3. computer  | 13. engine simulation                    |
| 4. wind tunnel design                                    | 14. horizontal stabilizer                |
| 5. data  | 15. flap system                          |
| 6. organization, storage, analysis                       | 16. continuous polar curves              |
| 7. wind tunnel monitoring & control                      | 17. data, tunnel and model control       |
| 8. $M_\infty$ test section                               | 18. optimal strategy                     |
| 9. corrections (wall, , suspension)                      | 19. partial optimization                 |
|  | 20. polar curve points substitution      |
| 10. model design   | 21. polar curves substitution            |
| 22. optimization using wind tunnel/concept on-line cycle |  |
| 23. concept  |  |

5. RECAPITULATION

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In the introduction, the important position of experimental aerodynamics within the development process is described. Here, an analysis of present practice in industrial wind tunnel operation shows a certain potential for improvement.

Using the existing development trends in aircraft design, e.g. the variable camber wing and laminarization and/or the closely associated subjects, such as the engine-airframe interference, the requirement for appropriate wind tunnel engineering is derived. Problems are handled which are associated with boundary layer simulation, flow quality, engine simulation and wind tunnel corrections. The European wind tunnels currently in existence are investigated from the standpoint of industry with respect to their suitability and quality, in which process the DNW and the planned ETW are given particular significance. For the

laminarization subject, alternative concepts must also be taken under consideration, for example free-flight measurements.

Generally, research methods, the required test technique and the needed wind tunnel modification measures are reported on.

In conclusion, the outlook is given for future more intensive coupling of experimental investigations in the wind tunnel with theoretical computer processes.

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